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Laser cooling of atoms and impact in theoretical physics

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Abstract Exchange of momentum during resonant interaction of laser radiation with atomic systems can decelerate the atoms and reduce their kinetic temperature Charged particles can be trapped by using a combination of electric and magnetic fields The cold ions have no first order Doppler effect This increases the precision of measurement in high resolution spectroscopy Collisions with buffer gas atoms in a Penning trap cool the cyclotron motion of ions but increase the magnetron radius leading to significant loss of ions in the trap It has been shown that application of an Rf field with frequency equal to the sum of the magnetron and cyclotron frequencies can lead to axialisation of ions thereby increasing the spatial overlap of the ions with the radiation and enhancing the sensitivity The method has been used for measurement of electronic and nuclear g-factors The high precision with which g-factors of fundamental particles is measured can be used as a test for results of QED calculations The new mechanism used for trapping of neutral atoms will be discussed This method has led to interesting new observations such as quantum jump, atomic fountains and Bose-Einstein condensation Observation of atomic parity violation experiments have led to the discovery of nuclear anapole moment

Keywords : Laser cooling, penning trap, g-factor, sisyphus cooling

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1. Introduction

"We never experiment with just one electron or atom. In thought experiments we sometimes assume that we do ; this invariably entails ridiculous consequences." – Schroedinger wrote in 1952 in an article "Are there quantum jumps ?".

More than twenty-five years after the development of quantum mechanics, Schroedinger had doubt if one could really see quantum jumps of Bohr which form the basic building block of quantum mechanics. However, the advancement of experimental methods and the availability of highly monochromatic and coherent laser sources have changed the scenario to such an extent that we are now capable of making measurements on a single electron or ion. This has enabled physicists to perform most precise measurements of fundamental particle properties and allowed us to see the quantum jumps in atoms. All these have become possible because

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laser radiations can be used to cool, stop, trap and probe atoms and ions.

Cooling and Trapping :

Cooling of an atom or an ion means reduction of velocity and hence the kinetic energy. To express the degree of cooling the kinetic energy of the particle in one dimension is equated to $kT/2$ and the velocity is expressed in terms of the temperature T. However, it should be understood that the word temperature means only the kinetic temperature and the macroscopic definition of temperature is not valid for a single particle or for a few particles.

Trapping means confinement of atoms in a small volume of space for a reasonably long period of time. The small volume of confinement is of the order of 1 cc or less. The period of confinement should be such that one can make measurements during the period. With the availability of pulse lasers of very short duration the confinement time of much less than a second can be considered long since a very large number of measurements can be made in this period.

Objectives :

The objectives of cooling and trapping of ions and atoms may be classified into two types : (i) Practical need to reduce the first order and second order Doppler shift in ultrahigh resolution spectroscopy and make high precision measurements. (ii) Dream of physicists to control the positions and velocities of atomic particles to within the limits imposed by quantum mechanics. The first objective has a definite aim, but the other arises from an aesthetic appeal to achieve something that is possible in principle.

2. Basic principle of Doppler cooling

The basic principle of laser cooling was originally formulated by Hansch and Schallow [1]. When an atom absorbs a photon it receives a series of momentum impulses in the direction of propagation of light beam. These momentum impulses add up to produce a scattering force which was first detected by Frisch [2]; he could deflect a beam of sodium atoms by light from a sodium lamp. The scattering force was too weak to confine atoms. The scattering force generated by laser light is much stronger. Hansch and Schallow used Doppler shift of radiation frequency to produce cooling. An atom is irradiated by two counterpropagating laser beams (Figure 1). The laser beam propagating opposite to the atomic velocity will appear to be shifted up in frequency. While the beam which is propagating in the same direction will appear to be shifted down in frequency. If the frequency of the radiation is detuned to a lower frequency the Doppler effect will push the oppositely moving wave towards resonance and the co-propagating

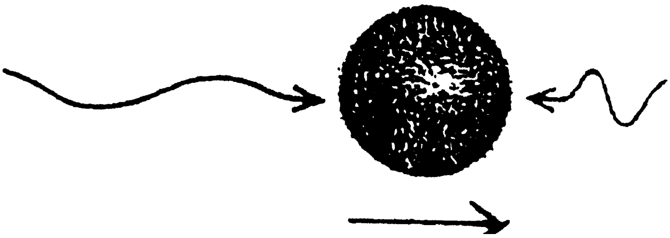

Figure 1. An atom moving along the z-direction with velocity v interacts with two counterpropagating laser radiations of the same frequency Due to Doppler shift in opposite directions the atom will face a viscous force.

radiation away from the resonance frequency. Hence, the atom has more probability of absorbing photons from the counter-propagating beam than from the other. As a result of absorption of the photon, the atom will be pushed back and will be decelerated. An atom which is moving in the opposite direction will also be slowed down by the other beam and will approach zero velocity. Soon after the absorption the atom emits a photon and this may push the atom in the direction of its velocity and may accelerate it. But this is a spontaneous process and the photons are emitted in all directions ; hence the net change of momentum produced is zero. This produces cooling of atoms in one dimension. By surrounding the atoms with three sets of mutually perpendicular laser beams the atoms can be cooled in three dimensions.

For each scattering event the atom receives a momentum $\hbar k$. The change in velocity of an atom of mass M per scattering event is $\hbar k$/M. There is some residual heating due to recoil. In the process of re-emission the average change of momentum is zero. But the atom makes a random walk in the momentum space as the momentum is transferred in each emission process. So the limiting kinetic energy of each atom is its recoil energy

$$E_R = (\hbar k)^2 \,/\, 2M . \tag{1}$$

Considering the conservation of energy and momentum [3] the net change in the kinetic energy of the atom is

$$\Delta E = \hbar k . v + 2E_R . \tag{2}$$

The first term produces cooling as k and v are in opposite directions ; the second term leads to heating. If the second term is smaller cooling will dominate. By considering the atomic cross-section for absorption and the velocity distribution of atoms one can calculate the rate of change of kinetic energy dE/dt. The minimum kinetic energy is obtained by putting $dE/dt = 0$. This lead to

$$E_{min} = \hbar \gamma / 4 \tag{3}$$

where γ is the natural linewidth. For sodium atom γ = 10 MHz and assuming $E = kT/2$, we get $T_{min} = 240\,\mu K$. This sets a lower limit of temperature that can be obtained by Doppler cooling.

3. Trapping of charged particles

Charged particles can be confined by Penning or Paul traps. Penning trap, developed by Wineland and Dehmelt in 1975 [4] is confinement of ions in the combination of a homogeneous magnetic and an electrostatic quadrupolar field. In the Paul trap a radio frequency field is used instead of a magnetic field. It was first used by Paul [5] for confinement of neutrons. We shall discuss only Penning trap here. It consists of a ring electrode and two endcaps (Figure 2). The ring electrode has the shape of a paraboloid so that a dc electric field applied across the endcaps and the ring electrode gives rise to a quadrupolar field [4]. The magnetic field is along the z direction. An ion inside such a trap will experience three kinds of motions. The cyclotron motion has a high energy and leads to rotation of the ions around the magnetic field direction. The electric field leads to an axial motion which is an osicllation in the z-direction. In addition to this there is slow rotation of the ion around the magnetic field direction in a circle of larger diameter. This is called magnetron motion. The oscillation frequencies of the three motions are

$$\omega_c = \frac{e}{mc} B,$$

$$\omega_z = \left(\frac{eV_0}{md^2}\right)^{1/2} \tag{4}$$

$$\omega_m = \omega_c / 2 - \left(\omega_c^2 / 4 - \omega_z^2 / 4\right)^{1/2},$$

V_0 is the dc electric field and d is a parameter depending on the dimension of the trap.

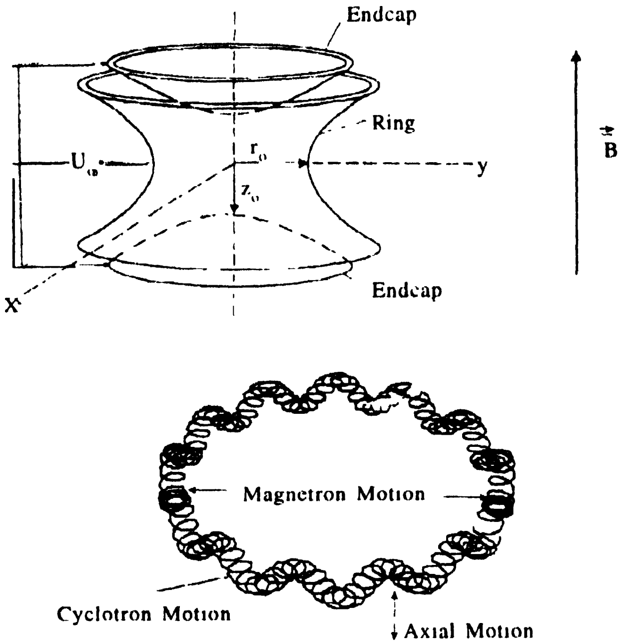

Figure 2. Penning trap. A dc electric field is applied between the endcaps and the ring electrode. The magnetic field B is applied along the z-direction. The lower figure shows the ion motion inside the trap as described in the text

Axialisation of ions in a Penning trap :

Collisions with buffer gas molecules dampen the ion oscillation so that they are decelerated and cooled and then trapped. The collisions reduce the radius of the cyclotron orbit ; but the magnetron radius is increased in the process. This is because the magnetron motion is unstable. The ions will move to the walls of the trap and this will lead to loss of ions. This is a limitation of buffer gas cooling. If an Rf field is applied at the sum frequency of the cyclotron and the magnetron motion two motions are coupled and energy exchange takes place. In this case both the magnetron and the cyclotron radii decrease and the ions are brought to the centre of the trap. This process of axialisation helps cooling as shown in the case of Ba^+ ions by Lichtenberg *et al* [6]. The axialisation leads to large increase in observation time and enhances the spatial overlap of the ions with the laser beam.

4. Precision measurements by a Penning trap

Charged particles which are loaded into the trap can remain trapped there virtually for ever. These particles execute cyclotron motion around the magnetic field direction. A small cloud of moving electrons trapped inside the cavity is like a many-electron atom called Geonium [7] where the atomic nucleus, is replaced by an external trapping field that can be adjusted. A single electron trapped in this way is analogous to a hydrogen atom. The geonium energy levels are split by interaction with the spin of the electron. The measurement of spectroscopic transition frequencies lead to very accurate values of electronic g-factor [8]. The most recent experimental value of electron g-factor is

$$g/2 = 1.001\ 159\ 652\ 188\ 4\ (43).$$

The theoretical value obtained by using the value of fine structure constant from quantized Hall effect *i.e.* $1/\alpha = 137.035997\ 9(32)$ is

$$g/2 = 1.001\ 159\ 652\ 140\ (27).$$

It may be noted that there is discrepancy in the twelfth place of decimal. According to the renormalisation theory of quantum electrodynamics the g-factor can be expanded in a power series of α / π. The uncertainty in the theoretical value arises from the uncertainty in the coefficient of expansion and also the uncertainty in the value of the fine structure constant. The ion trap experiment has also led to accurate value of g-factor of positron.

A comparison of proton and electron cyclotron resonance frequencies leads to accurate values of electron-proton mass ratio. Measurement of cyclotron frequencies of hydrogen and deuterium together with deuteron binding energy gives accurate value of neutron mass. Measurement of mass difference between 3H and 3He determines possible neutrino mass from tritium β-decay measurements.

Precise numerical values of fundamental particle properties are used to compare the predictions of theory with measurement. The comparisons of properties of particles and antiparticles provide a test of fundamental symmetries like CPT in physics. Any discrepancy of theoretical value from experimental data indicates limitations of the theory.

5. Trapping of neutral atoms

The neutral atoms have no charge ; electric or magnetic fields cannot be used for trapping them as easily as in the case of charged particles. Induced dipole forces are too weak to trap them for appreciably long time. It was first shown by Chu *et al.* [9] that three dimensional cooling of atoms by a configuration of six laser beams generate a strong viscous force. They called the laser configuration "Optical Molasses". The experiments were subsequently repeated by several other groups. But Phillips and coworkers [10] showed that in case of sodium atom the optical molasses could produce a temperature of 40μK much lower than the Doppler cooling limit of 240 μK. The explanation of this new phenomenon was given by Dalibard and Cohen-Tanoudji [11] and independently by Chu and coworkers [12]. The theory is based on a combination of three well-known concepts of physics : – optical pumping, light shifts and laser polarization gradients.

Optical pumping :

The atomic levels are not single, but have several Zeeman sublevels that are degenerate in the absence of external fields. These levels are the eigenvalues of the projections of the total angular momentum on a given axis. The sublevels having different values of angular momentum projection quantum number m have different selection rules depending upon the light polarization. This difference in selection rules results in selective population distribution of these levels. Thus they serve as the pathways of optical pumping. If we consider a ground state with $J = 1/2$ and an excited state with $J = 3/2$, there are two ground state levels with $m = 1/2$ and $m = -1/2$ and four excited state levels with $m = 3/2$, $1/2$, $-1/2$ and $-3/2$ (Figure 3). If the laser beam is circularly polarized in the clockwise direction the selection rule is $\Delta m = -1$, so the atoms in the $m = 1/2$ state will be taken to $m = -1/2$ upper state and they can decay back to the $m = -1/2$ or $1/2$ lower states. Those which come back to the $m = 1/2$ lower state will absorb another photon in the next process. After a series of absorption -spontaneous emission cycles all the atoms will eventually reach the state $m = -1/2$. Similarly, the atoms which start in the $m = -1/2$ lower state, will be taken to the $m = -3/2$ upper state and can decay only to the $m = -1/2$ lower state. Thus, the clockwise circularly polarized radiation will take all the atoms to the $m = -1/2$ state. On the other hand, if the light beam is circularly polarized in the counterclockwise direction a series of absorption-spontaneous emission cycles will take all the atoms to the $m = 1/2$ ground state. As a result of this optical pumping, a particular distribution of population and coherence can be achieved in the steady state depending on the laser polarization. The rate of optical pumping depends linearly on the laser intensity. So the optical pumping needs a finite time.

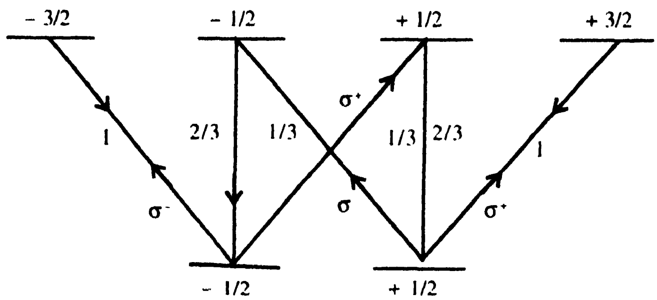

Figure 3. Optical pumping. The clockwise circularly polarized radiation σ and counterclockwise circularly polarized radiation σ^+ cause absorptions with different selection rules The figures 1/3, 2/3 and 1 describe the relative strength of the induced absorptions.

Light shifts :

The interaction of a strong radiation field with a quantized atomic system causes the atom-field energy levels to repel each other ; the magnitude of the shift of the levels is proportional to the light intensity and the transition strength. So the ground energy level is shifted downwards. Hence the light shifts depend on the laser polarization and the atomic sublevels involved in the transition.

Laser polarization gradients :

In the case of one-dimensional molasses two oppositely moving light beams with equal amplitudes and orthogonal linear polarizations produce a strong polarization gradient along the direction of propagation. The polarization changes from linear to clockwise circular polarization in a distance $\lambda/8$ and then again to linear and to counterclockwise circular polarization in each distance of $\lambda/8$. Thus over one half-wavelength the radiation has linear, clockwise circular, linear and counterclockwise circular polarizations (Figure 4).

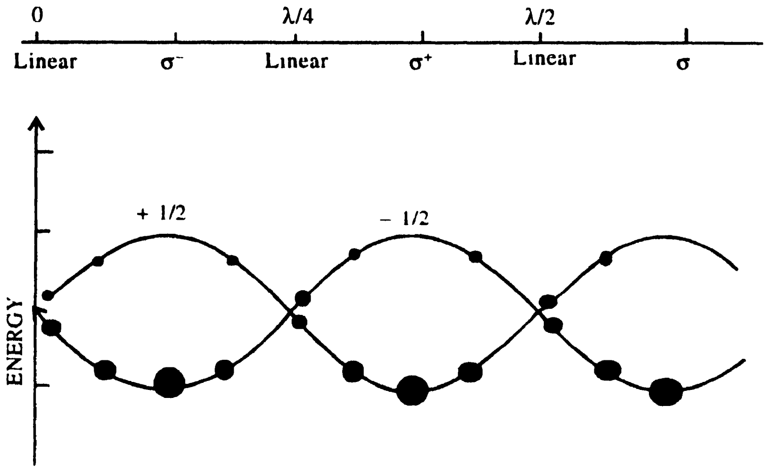

Figure 4. Laser polarization gradient and light shifts

Sisyphus cooling :

The polarization gradient causes the atoms located at different points on the z-axis (Figure 5) to have different selection rules and differential optical pumping. Thus the atoms at $z = \lambda/8$ will be pumped by clockwise polarized light to $m = -1/2$ state as explained above. The transition from the $-1/2$ state is three times stronger than the transition from the $m = 1/2$ state, so the light shift of the lower $-1/2$ state will be three times greater than that of the lower $1/2$ state, both of them are pushed down by the light shifts. At $z = \lambda/4$ the light is linearly polarized, so the two sublevels will be equally populated and will have the same light shifts. Since the laser radiation

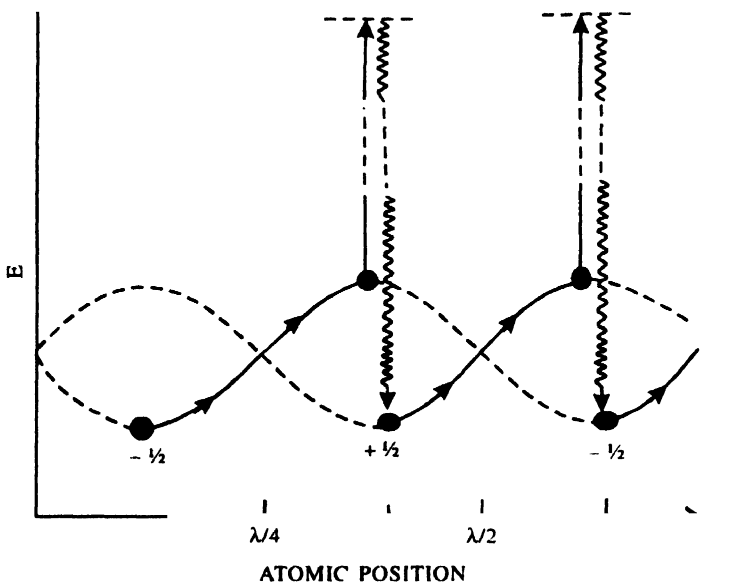

Figure 5. Sisyphus cooling. The atom faces an ever-climbing hill.

is counterclockwise polarized at a further distance of $\lambda/8$ the lower + 1/2 level will be populated and will have larger light shift. Thus the stationary atoms will have different population distributions and level shifts along the z-axis. When the atom moves the symmetry of the population distribution is changed. The optical pumping needs a finite time. If the time taken by the atom to travel a distance $\lambda/4$ is equal to the optical pumping time the atoms which are in the – 1/2 lower level will remain in the same level and will climb up the energy hill for a distance of $\lambda/4$ when the next optical pumping will take it down to the valley of the + 1/2 level. In the next cycle the atom will have to climb up again. Thus the atom has always to face an ever-climbing hill (Figure 5). In the process it has to do more work and will lose energy and get cooled. This phenomenon is known as *Sisyphus Effect.* The explanation given for one-dimensional motion can be extended to three-dimensional optical molasses and can explain the low temperature that could be obtained in the optical molasses.

6. Deceleration of atoms by gravity

Magneto-optic trap uses a magnetic field varying in space and circularly polarized light. Later Wieman and coworkers [13] used this trap with a glass cell and inexpensive diode lasers to trap atoms. Chu [14] used this trap to confine ten million atoms for 0.5 seconds. The ultra-cold atoms are then launched upward to create atomic fountain. The atoms with an initial velocity of nearly two meters per second are decelerated by gravity and are brought to zero velocity at an approximate height of $h = v^2/2g = 20$ cm. A microwave guide placed at this height will introduce microwave pulses to cause hyperfine transitions between the atomic levels of cesium. The microwave interacts with atoms which have almost zero velocity. The resolution of energy measurement is extremely high. This has enabled measurement of clock transitions with very high accuracy.

Bose-Einstein condensation :

Cold atoms have very low momentum p so the de-Broglie wavelength $\lambda = h/p$ becomes very large. Hence, the average size becomes comparable to the average distance between the atoms. At this low temperature and high density, a large fraction of all the atoms will condense into a single ground state leading to Bose-Einstein condensation. Laser cooling of atoms have made possible experimental observation of BEC in 1995 [15].

7. Conclusions

Light beams are used to decelerate atomic particles so that they can be trapped and their fundamental properties can be measured with an unprecedented accuracy. The high precision values are important for verification of theoretical values based on quantum electrodynamics.

Cooling of neutral atoms beyond the Doppler limit has thrown new challenges for atomic parity nonconservation measurements [16] and discovery of nuclear anapole moment [17]. These high precision experiments place constraints on the Standard model of physics.

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